Economic Feasibility of using by-products in soil stabilization, Saudi Arabia

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Abstract**—** *The rapid expansion in the civil and industrial activities in the eastern area of Saudi Arabia has made the improvement of local soils an indispensable task. It is essential for the designers and builders to be able to select an appropriate stabilizer to fulfill the engineering, environmental and economic requirements of the local soils. This study is to evaluate the economic utilization as well as the possibility of improving the mechanical properties of local soils utilizing indigenous industrial by-products, such as oil fuel ash (OFA), cement kiln dust (CKD) and electric arc furnace dust (EAFD). Three types of eastern Saudi soils, namely sand, non-plastic marl and sabkha, were treated with different dosages of the selected industrial by-products. The mechanical properties of the stabilized soils were evaluated by determining the unconfined compressive strength and the durability of the developed mixtures. Micro-characterization methods, such as x-ray diffraction (XRD) and scanning electron microscopy (SEM), were utilized to qualitatively study the mechanisms of soil stabilization due to the use of the selected industrial by-products.*

Results of this investigation indicated that non-plastic marl stabilized with 7% cement was found to be suitable for base course in rigid pavements while the same soil stabilized with 5% cement or with 30% EAFD plus 2% cement or with 30% CKD plus 2% cement was found to be suitable for sub-base course. Non-plastic marl stabilized with 20% EAFD plus 2% cement was found to be suitable as a sub-base in rigid pavements.

Dune sand stabilized with 7% cement or with 30% CKD plus 2% cement or with 20% EAFD plus 2% cement was found to be suitable for sub-base course in rigid pavements. Sand stabilized with 30% EAFD was found to be an appropriate material for sub-base in flexible pavements. However, sabkha stabilized with 7% cement or with 30% CKD plus 2% cement was found to be suitable for sub-base course in rigid pavements.

Keywords**— stabilization, by-products, XRD, SEM,Unconfined Compression Tests, CBR.**

I. INTRODUCTION

The rapidly growing population and industrialization in Saudi Arabia is exerting tremendous pressure on the construction industry to build the necessary infrastructure. The newly developed infrastructure is mostly concentrated along the coastal areas, mainly on weak soils. These soils need to be stabilized utilizing chemical and/or mechanical methods. Portland cement and lime are commonly utilized for chemical stabilization. Some other materials, such as fly ash, are also utilized for this purpose.

Since cement kiln dust (CKD), oil fuel ash (OFA) and electric arc furnace dust (EAFD) are considered as waste materials, it would be a noble task to use them in civil engineering applications, such as soil stabilization. Usage of these waste materials will result in:

1. Saving money;
2. Preserving the environment by beneficial utilization of these waste materials; and
3. Conserving the energy being utilized in the production of cement and lime.

There are four types of soil in the eastern province of Saudi Arabia, namely, clay, sabkha, marl and dune sand. Clayey soils are only located in limited regions in Al-Qatif and Al-Ahsa, further, these soils also well known to be treated with lime and, therefore, clay was excluded from this study. While marl is often being used in many projects in eastern Saudi Arabia, sabkha and dune sand are problematic soils and their usage in construction projects is risky and very limited. Therefore, this research was intended to investigate the possibility of incorporating CKD (cement by-product), OFA (produced during burning of heavy oil in power plants) and EAFD (by-product of manufacturing steel using electric arc furnace) for the stabilization of the three selected indigenous eastern Saudi soils, namely, non-plastic marl, dune sand and sabkha.

OBJECTIVES

The general objective of the proposed study was to assess the possibility of improving the engineering properties of

local soils utilizing indigenous industrial by-products. The specific objectives were the following:

1. To improve the mechanical properties and durability of eastern Saudi soils (i.e. non-plastic marl, dune sand and sabkha) utilizing indigenous industrial by-products, including oil fuel ash (OFA), cement kiln dust (CKD) and electric arc furnace dust (EAFD),
2. To study the mechanism by which the selected industrial by-products affect the properties of the local soils and
3. To develop charts, guidelines and/or models that would help the practicing engineers to select and estimate the appropriate dosage of the industrial by-product(s) in terms of strength, durability.
4. To determine the costs and economic utilization of the industrial by-product(s) in stabilizing the weak soils in steed of Cement.

To achieve these objectives, the selected soils were treated with different dosages of cement, CKD, OFA and EAFD. Cement was included to be a reference stabilizer. The stabilized soils were evaluated through macro-characterization tests, such compaction, CBR, unconfined compressive strength and durability. Micro-characterization studies were conducted utilizing SEM and XRD. Based on the results of these tests, models were developed to help the users to select the dosages of the stabilizers for each of the three selected local soils.

II. MATERIALS

2.1 Soils

2.1.1 Marl

Marl is considered to be one of the four predominant types of soils found in eastern Saudi Arabia (i.e., sand, marl, clay and sabkha). Due to the unsuitability of the other three soils, marl soils are uniquely used in the construction of almost all types of road bases, embankments and foundations. Many researchers [Netterberg, 1982; Qahwash, 1989; Al-Amoudi et al., 2010] defined marl as a soil or rock-like material containing about 35–65% calcareous material as well as varying percentage of clay. The term ‘‘marl” is often used to represent indefinitely all types of calcareous materials. Marl, being primarily calcareous in nature, is influenced by the mineral composition, type of parent carbonate mineral present, origin and the formation process, grain-size distribution and degree of cementation.

2.1.2 The sand dunes

Geographically, the sand dunes in the Arabian Peninsula are divided into three major zones. The great Al-Nafud in the north (57,000 km^2) links to Ar-Rub Al-Khali (the Empty Quarter) in the south (600,000 km^2) through the Arch Ad–Dahna that runs in another direction extending about 1,300 km. The sands of these two zones, Ad-Dahna and the great Al-Nafud, are medium to fine in size and bright red-orange in color due to a coating of iron oxide on the quartz grains. On the other hand, Ar Rub' Alkhali (Empty Quarter) sands are buff to tan in color due to the presence of carbonates. The primary source of most of the sands is the large granite batholiths underlying the Arabian shield [Al-Sayari and Zolt, 1978, quoted by Ahmed, 1995].

2.1.3 Sabkha

Sabkha is an Arabic word meaning salt flat and is applicable to both coastal and interior salt flats. There are two types of sabkha, sandy sabkhas and muddy sabkha. Sandy sabkhas are very loose to medium dense and may sometimes be partially cemented by salts. Muddy sabkhas are lagoon sediments consisting mainly of sandy carbonate mud. According to their location, sabkhas are found at coastal and inland (continental) areas [Juillie and Sherwood, 1983].

2.2 Stabilizers

Weak soils need to be stabilized in order to improve their mechanical properties and durability. Stabilization can be done mechanically or chemically. The selected stabilizers should be environment-friendly, easy to be used, available locally and economical.

The following sub-sections describe the industrial by-products used in this investigation.

2.2.1 Cement Kiln Dust (CKD)

Cement kiln dust (CKD) is generated during the manufacturing of cement clinker. As the raw feed travels through the Portland cement kiln system, particulates of the raw materials, partially processed feed, and components of the final product are entrained in the combustion gases flowing counter current to the feed. These particulates and combustion gas precipitates are collected in the particulate matter control device. The collected materials are referred to as cement kiln dust (CKD).

Generation of CKD is estimated to be about 30 million tons/year [Dyer et al., 1999]. Large quantities of CKD are produced during the manufacture of cement by the dry process. While modern dust-collecting equipment is designed to capture virtually all CKD and much of this material can today be returned to the kiln, for various reasons, a significant portion, in some cases as much as 30–50% of the captured dust, must be removed as industrial waste [Kessler, 1995 and USEPA, 1998]. As a result, in the United States, more than 4 million tons of CKD, unsuitable for recycling in the cement manufacturing process, require

disposal annually [Todres et al., 1992]. CKD contains a mixture of raw feed as well as calcite materials with some volatile salts. It is derived from the same raw materials as Portland cement but, as the CKD fraction has not been fully burnt, it differs chemically from the former. The chemical composition may, however, vary with the cement manufacturing process and type of the raw materials.

There are many cement factories in the Kingdom of Saudi Arabia that produce thousands of tons of cement daily. Some of these factories face a problem of producing large quantities of CKD, a Portland cement by-product. For example, the Arabian Cement Company Ltd. (ACCL), Jeddah, produces around 1,000 tons of CKD/day, which is expected to double after the completion of its expansion project. Due to the high levels of chlorides and alkalis in CKD, many cement manufacturers are reluctant to recycle CKD into the production line [Kessler, 1995; USEPA, 1998]. Though, the figures on CKD production are not precise. CKD production in Saudi Arabia was about 1.2-1.4 million ton/year in 1998. It has been projected to increase the cement production and the restrictions on air pollution in the Kingdom will be fully applied [Al-Refeai and Al-Karni, 1999].

Due to its chemical composition, CKD has a potential to be used in stabilization of eastern Saudi soils. Typical analyses for UK cements and CKD are given in Table 1**.**

Table 1: Typical Chemical Composition of CDK and Cement [Aidan and Trevor, 1995]

Constituent	**CKD (%)**	**OPC (%)**
Al_2O_3	3-6	5
CaO	38-50	64
Cl	0-5	<0.1
Fe_2O_3	1-4	3
Free CaO	1-10	2
K_2O	3-13	<1
Loss On Ignition(LOI)	5-25	1
MgO	0-2	1
Na_2O	0-2	<1
SiO_2	11-16	22
SO_3	4-18	3

2.2.2 Electric Arc Furnace Dust (EAFD)

Electric arc furnace dust (EAFD) is a by-product of smelting iron ore to separate the metal fraction from impurities. It can be considered to be a mixture of metal oxides and silicon dioxide. However, slag can contain metal sulfides and metal atoms in the elemental form. While slag is generally used as a waste removal mechanism in metal smelting, it can also serve other purposes, such as soil stabilizer, assisting in the temperature control of the smelting; and also minimizing any re-oxidation of the final liquid metal product before the molten metal is removed from the furnace and used to make solid metal. It can be used as stabilizer for concrete and mortar [Fredericci et al., 2000].

It is widely reported that about 20 kg of dust is produced for each ton of steel produced. It is a complex, fine-grained, high-density material containing high amounts of zinc and iron, and significant amounts of calcium, manganese, magnesium, lead and chromium.

There are four groups for steel production in Saudi Arabia: SABIC, Al Ettefaq, AlRrajhi and Al Yamama that produce crude steel. The annual production of steel in Saudi Arabia is about 5 million tons in 2012 and it is expected to increase in 2013 to 6.9 million tons [The Saudi Economist Magazine, 2012; Asharq Al-Awsat, 2012].

About 15 to 20 kg of EAFD is produced per ton of steel [Recupac, 2012]. Consequently, 100,000 tons of EAFD is produced annually. Therefore, slag, a steel by-product, is available and it would be wise to investigate the potential use of it for the improvement of the mechanical properties of eastern Saudi soils.Yildirim and Prezzi [2009] reported that the specific gravity of the EAFD is in the range of 2.71 to 3.04

2.2.3 Oil Fuel Ash (OFA)

Oil fuel ash is a powdery residue generated by the power stations that use heavy oil as the source of fuel. It consists of inorganic substances, such as SiO_2, Al_2O_3, Fe_2O_3, with 70~80% of unburned carbon and heavy metals, like vanadium and nickel, that are present in the crude petroleum at the initial stages.

Saudi Arabia has the largest proven reserves of oil in the world and it is available and economically feasible for generation of power. Saudi Arabia's Water and Electricity Ministry has estimated the demand of the country for electricity power to be at least 30 Gigawatts by 2023-25. Saudi Arabia is investing heavily in increasing the power and drinking water capacity. Shuaibah is the first power and water project in Saudi Arabia, and the first of a total of four planned major projects. The goal of these projects is to

increase the power plant capacity by 4,500 MW and to provide an additional 2.2 million cubic meters of drinking water daily [Najamuddin, 2011].

Saudi Arabia has been utilizing gas for power generation utilities as part of the government's plans to expand gas utilization. Moreover, it is also known that the biggest power plants in Saudi Arabia are fueled by oil. It is to be noted that Saudi Arabia is not utilizing, at the time being, coal or nuclear power, future plans will witness large increase in the use of oil as fuel for power plants [Dincer and Al-Rashed, 2002]. However, just like coal, which is being used for electric power generation in many countries, the process of power generation produces huge quantities of oil fuel ash as a solid waste.

The literature indicates a lot of research being undertaken to find ways and means of reusing the fuel ash produced from burning coal in the power plants. However, the fly ash produced from fuel oil is not widely investigated, which is different in many of its characteristics and chemical composition from the coal fly ash. Its contents of hydrocarbons, heavy metals, sulfur, and residue ash are different. Hence, its impact on the environment is different and its uses and ways of disposal are different. Therefore, further research studies are needed to explore ways and means of utilizing the heavy oil fuel ash and its safe disposal, particularly in Saudi Arabia, which produces large quantities of this type of ash. The typical physico-chemical properties of heavy oil fuel ash are as shown in Tables 2.

Table II: Typical Physico-Chemical Properties of Oil Fuel Ash [Kwon et al., 2005]

Constituent	**Percentage by Weight**
Carbon (C)	80.61
Hydrogen (H)	0.62
Nitrogen (N)	0.97
Magnesium (Mg)	0.02
Vanadium (as V)	0.44
Sulfur (as S)	3.5-5.16
Non-soluble in acid	84.79
PH 1 % solution	2.30
Ash	2.87-4.5
Residual moisture	7-9
Volatile matter	11.01

Oil fuel ash contains relatively high heavy metal content, particularly vanadium (as V_2O_5) and nickel (as NiO). In addition, the residual carbon level in the fuel ash is very high. Typical fuel oils contain Fe, Ni, V, and Zn, in addition to aluminum (Al), calcium (Ca), magnesium (Mg), silicon (Si), and sodium (Na). Transition metals [iron (Fe), manganese (Mn), and cobalt (Co)] and alkaline-earth metals [barium (Ba), calcium (Ca), and magnesium (Mg)] may also be added to the ash collector for the suppression of powder or for corrosion control [Bulewicz et al., 1974; Feldman1982, quoted by Abdulah, 2009].

Toxic heavy metals, such as vanadium (2.08% as V_2O_5) and nickel (0.37% as NiO) are also present in the heavy oil fuel ash. The high carbon content and presence of toxic heavy metals suggested that this oil fuel fly ash is a hazardous dust that requires careful handling and safe disposal to ensure proper environmental protection.

2.3 Additive Content and Specimen Preparation

In this investigation, the additive content is defined as the percentage of the weight of additive to that of oven-dry soil. Because cement is expensive, it is important to study and optimize the amount of the waste material that can replace or reduce the amount of cement required to stabilize soil in order to achieve targeted engineering properties, which depends on the soil type and its physical and chemical characteristics. Therefore, with maintaining maximum dry density, plain soil specimens, to serve as reference #1 and stabilized soil specimens, with varying dosages of the selected industrial by-products, were prepared with the optimum moisture contents from each soil sample. The dosages of industrial by-products that were studied are shown in the Table 3.

Table II-: Dosages of Stabilizers Studied

Stabilizer	**Dosage (by dry weight of soil)**
Cement (Reference)	2%, 5% and 7%
Cement Kiln Dust (CKD)	(i) 10%, 20% and 30% (ii) 2% cement plus 10%, 20% or 30% CKD
Oil Fuel Ash (OFA)	2% cement plus 5%, 10% or 15% OFA
Electric Arc Furnace Dust (EAFD)	2% cement plus 5%, 10%, 20% or 30% EAFD

Two percent cement by the weight of dry soil was added with the stabilizer content that could not improve the unconfined compressive strength of the stabilized soil (when it is used alone) to meet the strength requirement.

III. EVALUATION TECHNIQUES

In the macro-characterization study, modified proctor compaction test (ASTM D 1557), was conducted on

untreated and treated samples of the three soils to assess the optimum moisture content corresponding to the maximum dry density. Plain and stabilized soil specimens were prepared at the optimum moisture content and compacted with compaction energy that met the maximum dry density. The specimens were tested after a sealed curing period of 7 days (in order to maintain consistency in the results). The following standard tests were carried out on the plain and stabilized soil specimens:

- Unconfined compressive strength (ASTM D 2166);
- Soaked CBR (ASTM D 1883); and
- Durability (ASTM D 559).

The specimens that meet the strength, durability and environmental requirements, were utilized to qualitatively explain the mechanism behind the improvements achieved by the additives. This was done by conducting XRD and SEM. The macro-characterization tests are described in details in the following sub-sections.

IV. CHARACTERIZATION OF MATERIALS

The results of characterization tests conducted on the selected soils and industrial by-products are discussed in the following sub-sections.

4.1 Mineralogical Analyses

The mineralogical composition of the investigated soils (namely non-plastic marl, dune sand and sabkha) and the stabilizers were determined according to the procedures described in Chapter 3.

4.2 Mineralogical Composition of the Investigated Soils

The mineralogical composition of the investigated soils was performed using the X-ray diffraction (XRD) technique. Figures 4-1 through 4-3 show the X-ray diffractogram of the investigated soils.

Figure 4 shows the X-ray diffractogram of marl. These X-ray peaks therein reveal the presence of about 60% dolomite [$CaMg(CO_3)_2$], 30% quartz (SiO_2) and 6% calcite ($CaCO_3$) in addition to traces of other minerals. The relatively high percentage of calcite and quartz is responsible for the non-plastic and fine–grained nature of this type of marl [Al-Amoudi et al., 2010].

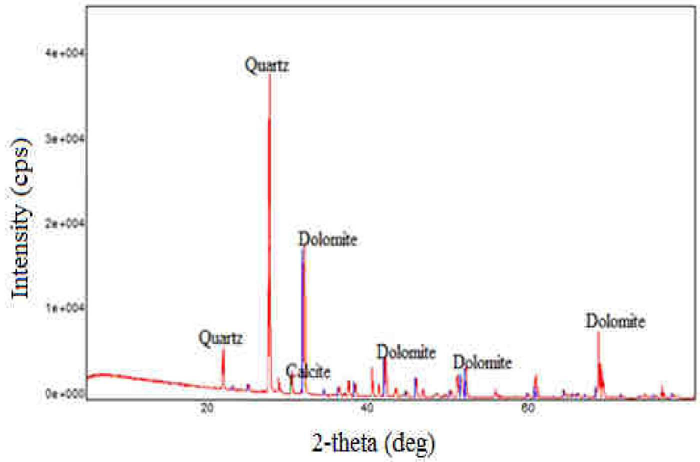

Fig.II: X-Ray Diffractogram for Non-Plastic Marl

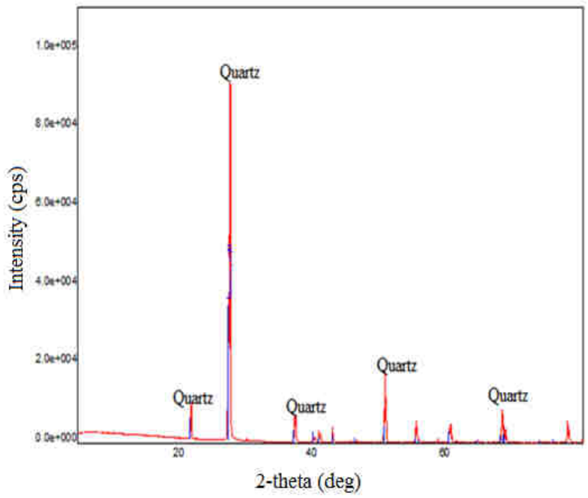

Fig.5: X-Ray Diffractogram for Dune Sand

Figure 5 shows the X-ray diffractogram for sand. The peaks for quartz were noted in this diffractogram. Quartz (SiO_2) constitutes about 100% of the sand.

Figure 6 shows the X-ray diffractogram for sabkha from Ras Al-Ghar. Peaks for quartz (75%), gypsum (12%) and halite (10%) were noted in addition to traces of other minerals.The high percentage of quartz is responsible for the non-plastic and fine–grained nature of this type of sabkha [Al-Amoudi et al., 2010].

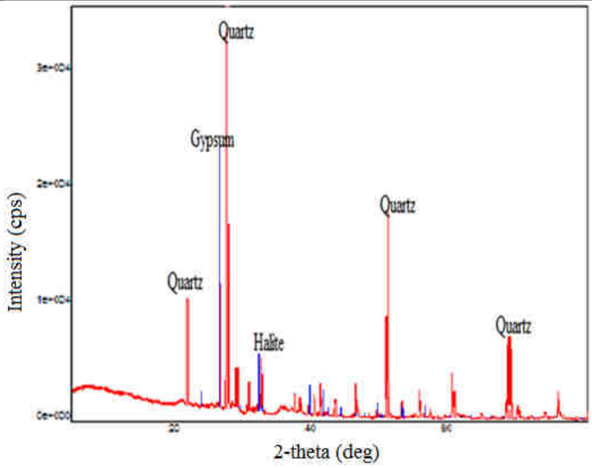

Fig.6: X-Ray Diffractogram for Sabkha

4.1.2. Chemical Composition of the Proposed Stabilizers

As stated earlier, ASTM C 150 Type I cement, CKD, EAFD and OFA were used as stabilizers. The chemical composition of these materials is summarized in Tables 4-1 through 4-3.

Table 7 : Chemical Composition of the Used CKD

Constituent	Weight %
CaO	49.3
SiO_2	17.1
Al_2O_3	4.24
Fe_2O_3	2.89
K_2O	2.18
MgO	1.14
Na_2O	3.84
P_2O_5	0.12
Equivalent alkalis (Na_2O + 0.658K_2O)	5.27
SO_3	3.56
Chloride	6.90
Loss on ignition, LOI	15.8
BaO (µg/g (ppm))	78.2
Cr_2O_3	0.011
CuO	0.029
NiO	0.012
SrO	0.37
TiO_2	0.34
V_2O_5	0.013
ZnO (µg/g (ppm))	65.8
ZrO_2	0.011

It is noticed from Table 1 that the used CKD contains 49% CaO, 17% SiO_2, 2.2% K_2O, 1.1% MgO and 3.6% SO_3 which constitute about 75, 80, 218, 1.14, 1.30 and 700%, respectively, of similar compounds in Type I Cement. Moreover; the LOI of the CKD is 15.8%, which can be considered very high compared with the ranges of the LOI value of the CKD, as shown in Table 2-2. A high loss on ignition (LOI) in the CKD implies that it contains a high amount of $CaCO_3$. When CKD is exposed to moisture, alkali sulfates quickly go into solutions. Free lime and some cementitious parts, if present, experience hydration. As a result, the availability of calcium ions is dictated by the equilibrium achieved through the solubility limit of$Ca(OH)_2$ and gypsum ($CaSO_4.2H_2O$) if present [Peethamparan et al., 2008]. Therefore, the high LOI in the current CKD probably indicates that it was exposed to moisture. It is well known that the lower the LOI is, the better will be the performance of CKD [Miller et al., 2003]. Furthermore, the current CKD contains 5.27% alkalis, which is about 4 times the alkalis in the Portland cement, as shown in Table 2. The data in Table 1 also show that the used CKD contains 6.9% chloride, which is more than in typical CKD.

Table 8 shows the chemical composition of the used EAFD. The most prevalent compounds are iron (Fe) about 34% and zinc (Zn) 10%. Furthermore, EAFD contains 9.4% of calcium (Ca) and 2.4% of silicon (Si) which are about 15 and 10% of similar compounds in Portland cement, respectively. Since lime and silicon are the main compounds that provide the cementitious compounds in Portland cement, the low content of these compounds indicates that EAFD may not provide adequate bonding. Therefore, 2% cement, by weight, was added to EAFD-soil mixtures. The increased quantity of cadmium (Cd), lead (Pb) and nickel (Ni) in the EAFD indicate that this stabilizer may contribute to heavy leaching of "hazardous" metals to the surrounding ground water.

Furthermore, the quantity of magnesium (Mg) is 2.3%, which is more than two times the quantity of this element in the ordinary Portland cement.

The data in Table 3 indicate that the LOI in the OFA is extremely high (61%) and the equivalent alkalis is very low compared to the ordinary Portland cement, as shown in Table 7 . Similarly, the quantity of sulfur (S) in the OFA is almost six times that noted in the ordinary Portland cement.

Table 8: Chemical Composition of the Used EAFD

Constituent	**Weight %**	**Constituent**	**Weight %**
Aluminium	0.7	Nickel	0.01
Calcium	9.39	Lead	1.31
Cadmium	0.0004	Phosphorous	0.13
Copper	0.06	Silicon	2.38
Iron	33.6	Tin	0.03
Potassium	1.7	Sulphur	0.57
Magnesium	2.3	Titanium	0.09
Manganese	1.8	Zinc	10
Sodium	2.6	Oxygen	33.33

Furthermore, it is also noticed, from the data in Table 4-3, that OFA contains high quantities of magnesium (Mg) and sulfur (S). Moreover; it contains relatively high quantity of heavy metal, particularly vanadium (as V2O5). Typical fuel oils contain Fe, Ni, V, and Zn, in addition to aluminum (Al), calcium (Ca), magnesium (Mg), silicon (Si), and sodium (Na). Transition metals [iron (Fe), manganese (Mn), and cobalt (Co)] and alkaline-earth metals [barium (Ba), calcium (Ca), and magnesium (Mg)] may also be added for the suppression of soot or for corrosion control purposes [Bulewicz et al., 1974; Feldman, 1982, quoted by Abullah, 2009]. From the chemical analysis of OFA (Table 9) it is evident that it contains small quantities of calcium and silicon, required to produce cementing gel, C-S-H. Consequently, 2% cement was added to OFA-soil mixture to improve the cementing property of OFA.

Table 9: Physco Properties of the Used OFA

Constituent	**Weight %**
SiO_2	1.65
CaO	0.45
Al_2O_3	< 0.10
Fe_2O_3	0.47
MgO	17.48
K_2O	0.03
Na_2O	0.53
V_2O_5	2.65
SO_3	9.60
Equivalent alkalis	0.55
(Na_2O + 0.658K_2O)	60.60
Loss on ignition	5.90
(LOI)	
Moisture content	

4.2. Specific Gravity

Specific gravity of the investigated soils and industrial by-products is summarized in Table 10.

Table 10: Specific Gravity of the Investigated Soils and the Stabilizers

Material	**Specific Gravity**
Marl	2.69
Sand	2.63
Sabkha	2.71
Cement*	3.15
Cement Kiln Dust*	2.79
Electric Arc Furnace Dust	2.76
Oil Fuel Ash*	1.30

- As reported by the suppliers

The specific gravity of non-plastic marl soil is 2.69 which falls in the range of 2.64-2.92, as reported by Ahmed [1995]. Similarly; the specific gravity of sand is 2.63 which falls in the range of 2.62-2.70, as reported by Al-Guniayan [1998]. The specific gravity of the sabkha is 2.71, which is lower than the value of 2.73 reported by Al-Amoudi, [1994], and it falls in the range of 2.51-2.82, as reported by Amin [2004]. Generally; the specific gravity of the investigated soils falls in the range of eastern Saudi soils. The specific gravity of EAFD is 2.76 which falls in the range of 2.71-3.1, as reported by Yildirim and Prezzi [2009].

The specific gravity of CKD and OFA is 2.79 and 1.30, respectively.

4.3Atterberg Limits of the Investigated Soils

It was not possible to get the required moisture contents for the 25 of blows for the liquid limit test for the investigated soils. Consequently, the liquid limit for the three soils was reported as "not defined". The three soils also could not be

rolled to a thread of 1/8-in (3.18 mm). Therefore, the investigated soils were classified as "non-plastic".

4.5 Grain Size Distribution and Classification of the Investigated Soils

The classification of the investigated soils was based on the grain-size analysis and the plastic indices.

4.5.1 Grain Size Distribution and Classification of Marl

Figure 4-4 indicates that the grain-size curve obtained by wet sieving method was consistently above the one determined by dry sieving method. This is attributed to the fact that water tends to dissolve the salts between particles of the soil, thus, the proportion of wet materials passing a particular sieve is consistently more than that for dry sieving.

It can be seen from Figure 10 that the soil passing sieve ASTM #200 is 22 and 28%, respectively, when dry and wet sieving methods were used. The soil can be classified as SM or SC if the material passing #200 is more than 12%. However, since the investigated soil was non-plastic (i.e. PI is less than 4), the soil is classified as SM and A-3 according to the USCS and AASHTO soil systems, respectively, based on both dry and wet sieving methods.

4.5.2 Grain Size Distribution and Classification of Sand

The grain-size distribution curves for the sand are depicted in Figure 11. It can be seen that there is almost no variation between grain size distributions determined by both the dry and wet sieving methods. This is ascribed to the fact that sand is made up of quartz which is not affected much by washing. Since the material passing #200 for the dry and wet materials was less than 5%, it could be classified as SW or SP, according to the USCS. The coefficients of uniformity (C_u) determined by dry and wet sieving methods is almost the same, 3.1. Therefore, sand is classified as SP.

Moreover; since the sand is non-plastic in nature, it can be classified as A-3 according to the AASHTO system.

4.5.4 Grain Size Distribution and Classification of Sabkha

The grain-size distribution curves for the sabkha soil are depicted in Figure 12. It can be seen that there is a large variation between grain size distribution curves determined by the dry and wet sieving methods. The material passing #200 was 10.2% and 32.7% for dry and wet sieving methods, respectively. The difference in the grain size distribution curves may be ascribed to the fact that sabkha is made up of quartz and soluble minerals which are largely affected by washing. Water tends to dissolve the bonds and salts between particles of the soil; thus, the material passing by wet sieving is much more than that by dry sieving [Al-Amoudi, 1994].

Since the material passing sieve #200 is less than 50%, the investigated can be classified as SM or SC according to USCS system. Since the collected sabkha is non-plastic, PI < 4, therefore, it can be classified as SM according to the USCS system and since it is non-plastic, it can be classified as A-3 according to the AASHTO system for dry sieving.

The material passing sieve #200 by wet sieving is 32%, (greater than 12%). Therefore, the wet sabkha can be classified as SM or SC. But the collected sabkha is non-plastic, PI < 4, hence, the wet sabkha is classified SM according to the USCS system and A-3 according to the AASHTO system.

In summary; the three investigated soils were classified as A-3 according to AASHTO system since none of those soils could be rolled to a thread of 1/8-in (3.18 mm).

Furthermore, as long as the percent passing ASTM sieve #200 was less than 5% for wet and dry sand samples, there was no need for running hydrometer analysis.

Similarly; the percent passing ASTM sieve #200 was less than 50% and greater than 12% for both marl and sabkha. In addition, both marl and sabkha soils are proven to be non-plastic; hence there was no need to carry out hydrometer analyses, for these materials as well.

ISSN: 2349-6495

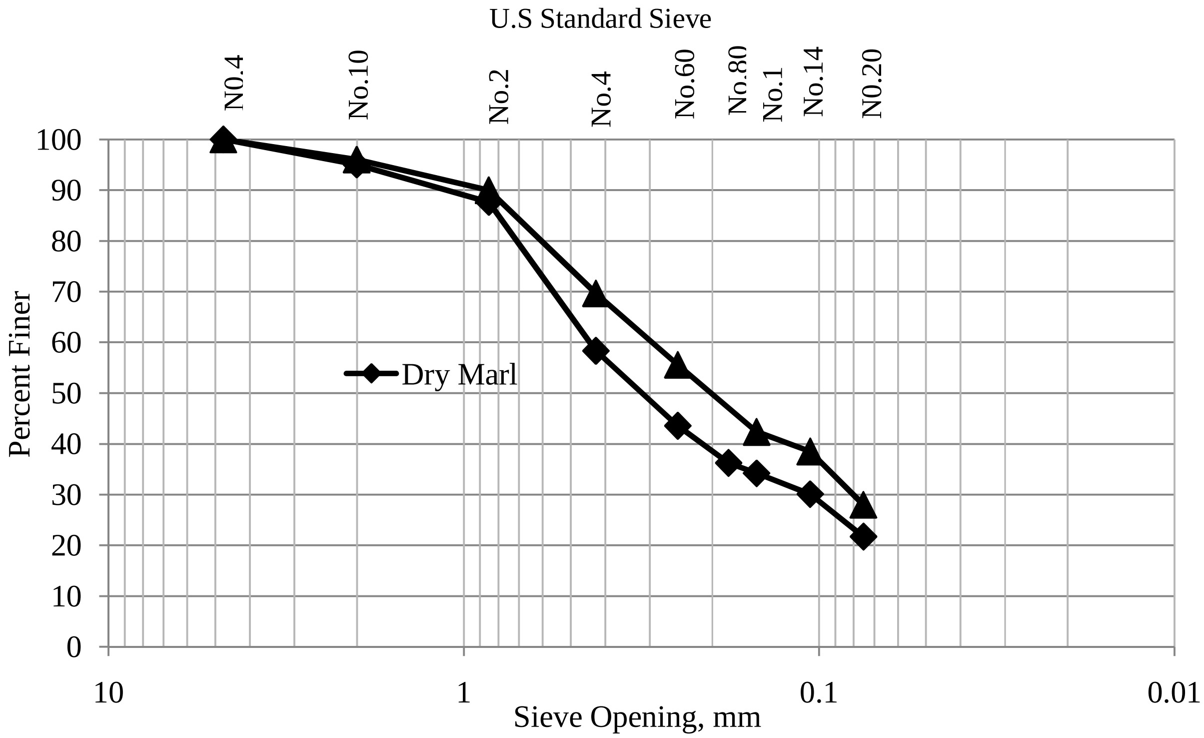

Fig.10: Grain Size Distribution of Marl

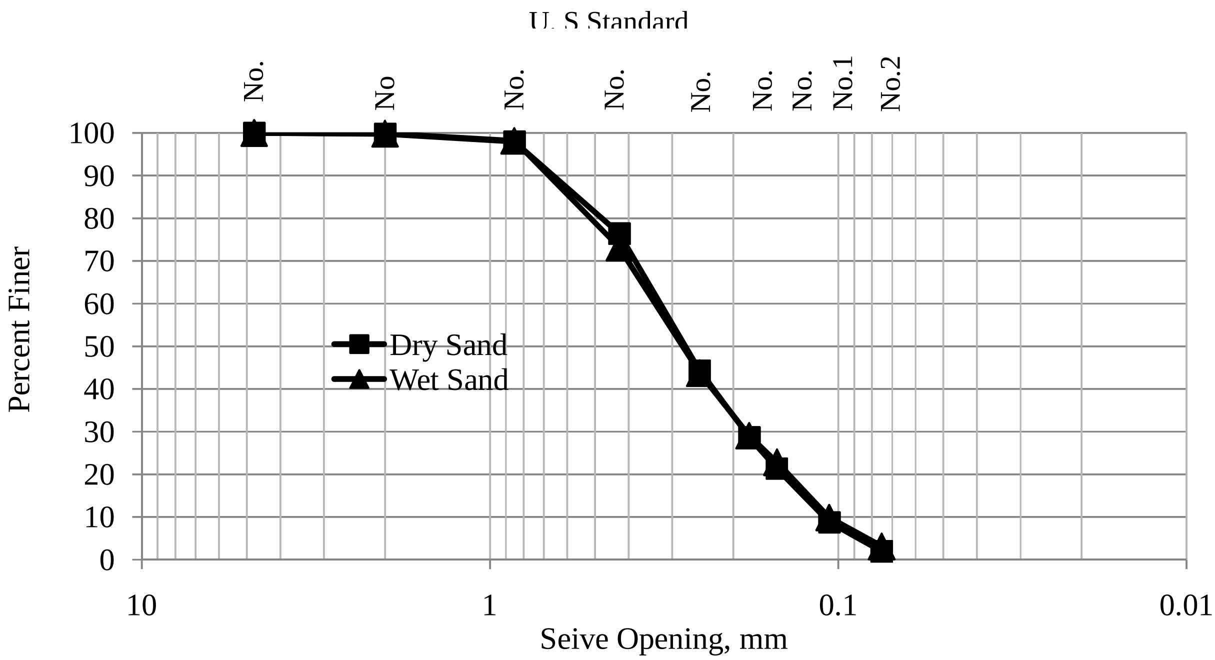

Fig.11: Grain Size Distribution of Sand

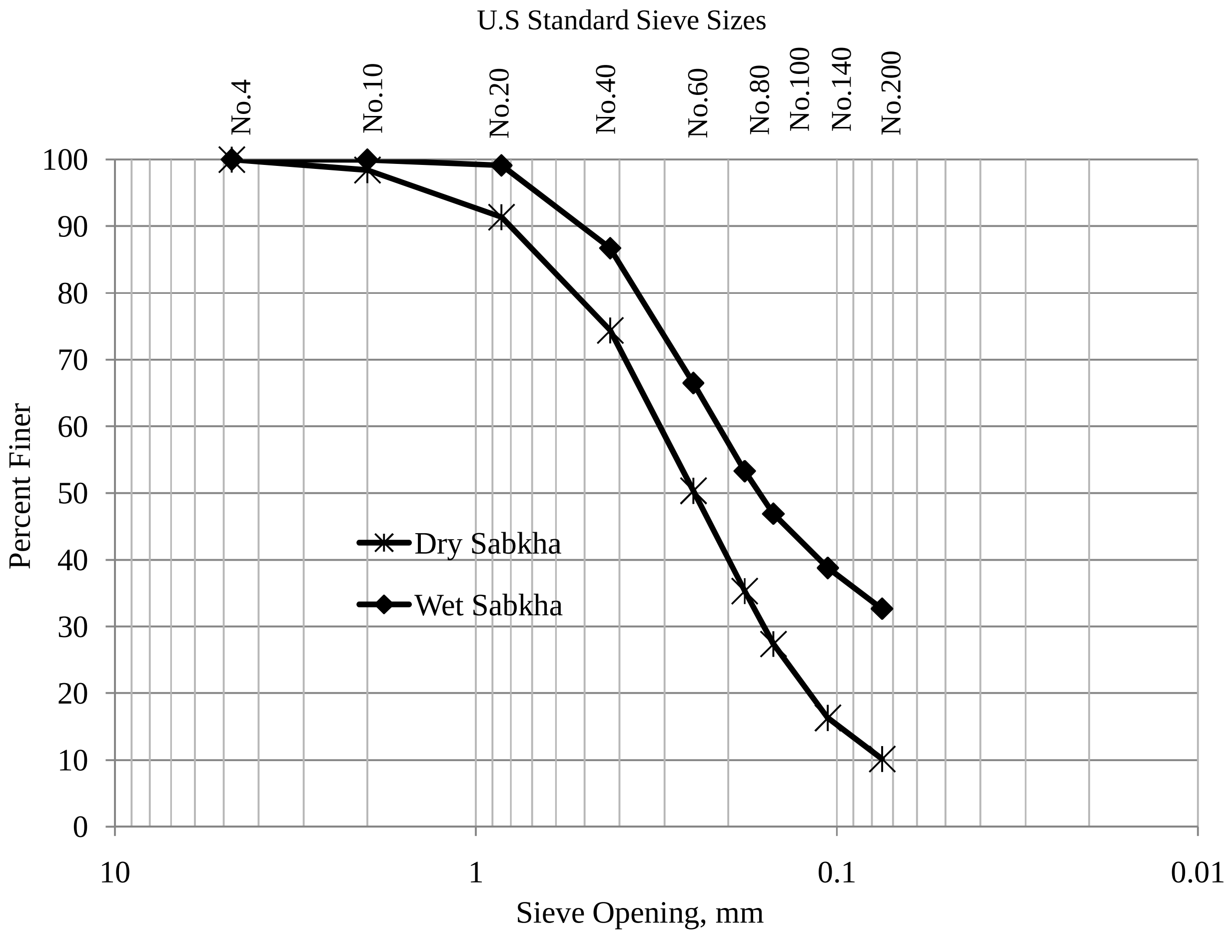

Fig.12: Grain Size Distribution of Sabkha

V. COMPACTION TEST RESULTS OF CEMENT-STABILIZED SOILS

5.1 Compaction Test Results of 2% Cement plus CKD - Stabilized Marl

Compaction tests were conducted on marl with 2% cement and with the addition of cement and CKD. The CKD addition was in the range of 10 to 30%. From the data in Figure 4-13, it can be noticed that the addition of CKD to non-plastic marl plus 2% cement resulted in an increase in the maximum dry density. The maximum dry density of the marl-stabilized with 2% cement plus 10, 20 and 30% CKD was 1.98, 1.98 and 1.95 g/cm^3, respectively. The maximum dry density of marl with 2% cement was 1.90 g/cm^3. This increase was due to the fact that the specific gravity of CKD (2.79) is higher than the specific gravity of non-plastic marl (2.69). The addition of 10 and 20% CKD has caused same increment in the maximum dry density. While the 30% of CKD has caused less increment in the maximum dry density less than the 10 and 20% CKD had. That was probably due to the fact that 30% CKD has damaged the gradation of the marl which reduced the maximum dry density [Abdullah, 2009].

Furthermore, CKD addition has caused a marginal increase in the optimum moisture content in the marl-cement-CKD mixtures. The optimum moisture content in 0, 10, 20 and 30% CKD with 2% cement was 7.6, 8.4, 8.4 and 10.0%, respectively. While the optimum moisture content in the 0, 10 and 20% CKD mixture was almost similar, it was significantly increased in the 30% CKD mixture. This has probably decreased the unit weight of the 30% CKD mixture.

5.2 Compaction Test Results of 2% Cement plus EAFD - Stabilized Sand

The effect of EAFD content on the dry density–moisture content relationship of sand with 2% cement was carried out using the modified compaction tests. The tests were conducted on sand with 2% cement as well as on sand with 2% cement and EAFD. The EAFD additions were in the range of 5 to 30%.

The data indicate that as the quantity of EAFD in the sand-2% cement mixture increases, the maximum dry density increases. The maximum dry density of the investigated sand plus 2% cement mixtures increased from 1.78 g/cm^3 to 1.90, 1.93, 2.08 and 2.19 g/cm^3, respectively, due to the addition of 5, 10, 20 and 30% EAFD. That was expected since the EAFD has higher specific gravity (2.76) than that of the sand (2.63).

The data also indicate that as EAFD content increases the optimum moisture content marginally decreases. The optimum moisture contents of sand with 2 % cement was 10.0 9.0, 9.2, 9.4 and 7.8% for EAFD contents 0, 5, 10, 20 and 30%, respectively. This was probably due to the fact that the investigated sand is of poor gradation, SP, and the EAFD powder is very fine material which fills up the voids within the sand particles thereby leading to a reduction in the volume of water needed for the lubrication.

5.3 Compaction Test Results of 2% Cement plus OFA-Stabilized Sabkha

Compaction tests were performed on sabkha stabilized with 2% cement plus 5 to 15% OFA.. The data indicate a decrease in the maximum dry density and an increase in the optimum moisture content with increasing quantity of OFA. The maximum dry density of sabkha with 2% cement plus 0, 5, 10 and 15% OFA was 1.96, 1.88, 1.77 and 1.75 g/cm^3, respectively. The decrease in the maximum dry density may be attributed to fact that the specific gravity of OFA (1.30) is less than that of sabkha (2.71).

It is also to be noted that the optimum moisture content of sabkha with 2% cement plus sabkha with 2% cement plus 0, 5, 10 and 15% OFA was 10.8, 11.4, 14.4 and 15.6%, respectively. The increase in the optimum moisture content may be attributed to the fact that OFA is a very fine material and, Consequently, it requires more water for lubrication.

In summary; the addition of OFA to the investigated soils with 2% cement caused variation in the maximum dry density. It decreased the maximum dry density of marl and sabkha with 2% cement which is ascribed to the lower specific gravity of the OFA compared to that of the marl and sabkha. However, OFA addition to the 2% cement-sand mixture increased the maximum dry density which was attributed to the fact that sand is of poor gradation, SP, and the OFA addition contributed to rearrangement of the sand particles which, in turn, increased the maximum dry density. Further, the addition of OFA to soils increased the optimum moisture content which may be attributed to the fact that OFA is very fine and more amount of water is required for lubrication.

Table 11 summarize the optimum moisture content and the corresponding maximum dry density for the three investigated soils stabilized with the proposed stabilizers.

Table 11: Summary of the Compaction Results of the Investigated Soils

Additive Type and Content	**Marl**		**Sand**		**Sabkha**	
	Υ_d (g/cm^3)	w_{opt} (%)	Υ_d (g/cm^3)	w_{opt} (%)	Υ_d (g/cm^3)	w_{opt} (%)
Plain (No Additive)	1.89	10.4	**	**	1.95	10.8
2% Cement	1.90	7.6	1.78	10.0	1.96	10.6
5% Cement	1.94	8.4	1.83	11.2	1.98	10.0
7% Cement	1.98	9.0	1.87	12.0	1.99	9.7
10% CKD	1.93	8.0	1.91	9.0	1.93	11.2
20% CKD	1.96	7.8	1.96	7.0	1.89	12.5
30% CKD	1.91	7.7	1.99	6.6	1.88	12.8
2% Cement + 10% CKD	1.98	8.4	1.92	9.2	1.93	9.8
2% Cement + 20% CKD	1.98	8.4	1.96	7.6	1.84	11.2
2% Cement + 30% CKD	1.95	10.0	1.97	7.4	1.85	12.2
2% Cement + 5% EAFD	2.00	9.2	1.90	9.0	1.97	10.6
2% Cement + 10% EAFD	2.04	9.0	1.93	9.2	1.97	10.8
2% Cement + 20% EAFD	2.10	8.8	2.08	6.4	1.98	11.2
2% Cement + 30% EAFD	2.23	8.0	2.19	7.8	1.99	11.2
2% Cement + 5% OFA	1.88	10.2	1.79	10.0	1.88	11.4

ISSN: 2349-6495

2% Cement + 10% OFA	1.80	12.2	1.80	10.1	1.77	14.4
2% Cement + 15% OFA	1.72	14.0	1.82	10.4	1.75	15.6

** Not conducted

5.4 Results of the Unconfined Compression Tests of Non-Plastic Marl

Table 12: UCS of Marl with Cement and/or Cement plus Stabilizer (7-Days Sealed Curing)

Additive Type and Content	UCS (kPa)		
	Specimen #1	Specimen #2	Average
Plain Marl (No Additive)	58	64	61
2% Cement	620	668	644
5% Cement	2,250	2,416	2,333
7% Cement	3,890	4,016	3,953
10% CKD	355	379	367
20% CKD	760	840	800
30% CKD	990	1,110	1,050
2% Cement + 10% CKD	940	960	950
2% Cement + 20% CKD	1,275	1,305	1,290
2% Cement + 30% CKD	1,760	1,800	1,780
2% Cement + 5% EAFD	665	687	676
2% Cement + 10% EAFD	870	882	876
2% Cement + 20% EAFD	1,405	1,449	1,427
2% Cement + 30% EAFD	2,404	2,456	2,430
2% Cement + 5% OFA	260	264	262
2% Cement + 10% OFA	228	236	232
2% Cement + 15% OFA	788	816	802

The unconfined compression tests were carried out on prepared specimens of plain and stabilized marl with varying amounts of each type of the proposed stabilizers. The results of the UCS for untreated and treated non-plastic marl are summarized in Table 12. The data in Table 4-6 indicate that plain non-plastic marl shows very low UCS and it should be stabilized prior to be used as a construction material for pavements.

5.4.1 Results of Soaked CBR Tests on Non-Plastic Marl

Specimens of marl treated with cement alone or with 2% cement plus stabilizer that fulfilled the minimum strength requirements specified by the ACI [1990], as well as of plain marl (as reference), were subjected to soaked CBR tests. Specimens were prepared and tested according to ASTM D 1883. The specimens were sealed and cured for seven days at laboratory condition (22 ± 3^{o}C). Then, they were soaked in tap water for 96 hours before testing. The effect of each stabilizer on the soaked CBR of non-plastic marl is discussed in the following table (12).

Table 12: CBR of Marl with Cement and/or Cement plus Stabilizer

Additive Type and Content	UCS (kPa)	Soaked CBR (%)		
		Specimen # 1	Specimen # 2	Average
Plain Marl (No Additive)	61	8	12	10
2% Cement	644	50	70	60
5% Cement	2,333	235	265	250
7% Cement	3,953	578	602	590
2% Cement + 10% CKD	950	92	98	95
2% Cement + 20% CKD	1,290	151	129	140
2% Cement + 30% CKD	1,780	282	288	285
2% Cement + 5% EAFD	676	144	162	153
2% Cement + 10% EAFD	876	179	193	186
2% Cement + 20% EAFD	1,427	293	301	297
2% Cement + 30% EAFD	2,430	299	309	304

A significant improvement in the soaked CBR (60, 250 and 590%) was noted in the marl with 2, 5 and 7% cement addition, respectively. Similarly; the soaked CBR improvement was very good (95, 140 and 285%) in marl stabilized with 2% cement plus 10, 20 or 30% CDK, respectively. Furthermore, the soaked CBR of 2% cement plus5, 10, 20 or 30% EAFD was 153, 186, 297 and 304% respectively.

5.4.2 Results of the Durability Tests on Stabilized Non-Plastic Marl

ASTM D 559 durability tests were conducted on the investigated marl that had satisfied the minimum strength requirements of ACI [1990]. The data in Table 4-9 summarize the weight loss in the various stabilized non-plastic marl mixtures. From the data in this Table, it is clear that as the cement content increases, the weight loss decreases significantly. The same trend is noticed for the EAFD content plus 2% cement. The highest weight loss, 8.9%, occurred for non-plastic marl stabilized with 20% EAFD plus 2% cement. The lowest weight loss was noted for marl stabilized with 7% cement. The weight losses are 0.4 and 2.7% for the cement contents of 5 and 7%, respectively, which are almost equal to what were reported by Ahmed [1995]. However, Al-Amoudi et al. [2010] reported that the weight loss was 2 and 4.8% for the cement content of 7 and 5%, respectively. The reported high weight loss in this investigation was probably due to the inferior quality of the investigated marl.

All the measured weight losses shown in Table 13 are below the maximum allowable weight loss of 14% according to the Portland Cement Association (PCA) and of 11% according to USA Corps of Engineers (USACE) for soils classified as SP and soils having, plasticity index, PI < 10, respectively [ACI, 1990]. Therefore, the mentioned stabilizers and dosages in Table 13 are appropriate not only from strength point of view but also from durability perspective.

Table 13: Weight loss of Stabilized Marl

Additive Type and Content	**Weight Loss (%)**
5% Cement	2.7
7% Cement	0.4
2% Cement + 30% CKD	8.2
2% Cement + 20% EAFD	8.9
2% Cement + 30% EAFD	7.8

5.4.3 Results of TCLP Tests on the Stabilized Non-Plastic Marl

EAFD contains some toxic elements, such as cadmium, lead and nickel, as shown in Table 4-2. The dosages of 20 and 30% of this stabilizer mixed with 2% cement improved the strength and durability of the non-plastic marl so as to satisfy the strength and durability requirements. Therefore, toxicity characteristics leaching procedures (TCLP) were carried out to study the environmental impact of using this stabilizer. The maximum allowable and measured concentrations of the toxic elements in the investigated marl stabilized with the EAFD contents of 20 and 30% plus 2% cement, are summarized in Table 14

In summary; the 20 and 30% EAFD plus 2% cement dosages are not only appropriate stabilizers for non-plastic marl from strength and durability aspects, but also from environmental point of view.

Table 14: TCLP for Marl Stabilized with 2% Cement + EAFD

Metal		EPA Limits	Measured Value	
			20 % EAFD	30 % EAFD
Name	Symbol	(mg/l)	(mg/l)	(mg/l)
Silver	Ag	5	0.007	0.012
Arsenic	As	5	0000	0000
Barium	Ba	100	1.008	1.043
Cadmium	Cd	1	0.575	0.669
Chromium	Cr	5	0.002	0.003
Mercury	Hg	0.2	0.014	0.017
Lead	Pb	5	0.119	0.174
Selenium	Se	1	0.094	0.101
Nickel	Ni	NR	0.038	0.043
Vanadium	V	NR	0000	0000

NR: Not regulated by EPA

5.4.4 Results of the Unconfined Compression Tests of Sand

Since the investigated sand is pure quartz and a non-cohesive material, it does not alone have any unconfined compressive strength. Therefore, sand with 2% cement was considered as the reference for relative comparison. Prepared specimens of sand stabilized with the proposed stabilizer types and content were sealed cured for 7-days at laboratory condition (22 ± 3 ^{0}C) before testing.

From the data in Table 15, it is evident that sand with 7% cement or sand with 2% cement plus 30% CKD, 20% or 30% EAFD met the ACI strength requirements mentioned in Table 3-2. It is evident that the addition of 30% CKD or 20-30% EAFD decreased the cement by about 5%. This reduction in the cement will decrease the cost of sand stabilization and also reduce the greenhouses gas emission.

Table 15: UCS of Sand with Investigated Additives (7-Day Sealed Curing)

Additive Type and Content	UCS (kPa)		
	Specimen # 1	Specimen # 2	Average
2% Cement	360	378	369
5% Cement	950	1,060	1,005
7% Cement	1,710	1,728	1,719
10% CKD	99	107	103
20% CKD	398	402	400
30% CKD	738	752	745
2% Cement + 10% CKD	412	424	418
2% Cement + 20% CKD	795	805	800
2% Cement + 30% CKD	1,372	1,390	1,381
2% Cement + 5% EAFD	386	398	392
2% Cement + 10% EAFD	529	535	532
2% Cement + 20% EAFD	1,390	1,464	1,427
2% Cement + 30% EAFD	2,412	2,426	2,419
2% Cement + 5% OFA	36	42	39
2% Cement + 10% OFA	45	49	47
2% Cement + 15% OFA	113	117	115

5.4.5 Results of Soaked CBR Tests on Stabilized Sand

Specimens of sand treated with 2% cement and sand stabilized with the stabilizers that satisfied strength requirements were prepared and tested according to ASTM D 1883. The effect of each stabilizer on the soaked CBR of sand is discussed in the following table (Table 16).

Table 16: Soaked CBR Results for Sand

Additive Type and Content	UCS (kPa)	Soaked CBR (%)		
		Specimen#1	Specimen#2	Average
2% Cement (Reference)	369	159	183	171
5% Cement	1,005	250	266	258
7% Cement	1,719	428	448	438
2% Cement + 10% CKD	418	180	198	189
2% Cement + 20% CKD	800	280	286	283
2% Cement + 30% CKD	1,381	388	404	396
2% Cement + 5% EAFD	392	181	195	188
2% Cement + 10% EAFD	532	365	395	380
2% Cement + 20% EAFD	1,427	532	550	541
2% Cement + 30% EAFD	2,419	737	763	750

5.4.6 Results of the Durability Tests on Stabilized Sand

ASTM D 559 durability tests were conducted on specimens of sand stabilized with the type and the content of the proposed stabilizers that satisfied the minimum UCS requirements specified by ACI [1990]. The results are summarized in Table 17. The results indicated that the highest weight loss, 9.1%, occurred in sand stabilized with 20% EAFD plus 2% cement. The lowest weight loss, 6.1%, was measured in sand stabilized with 7% cement. The weight loss was 6.7% in sand stabilized with 30% CKD plus 2% cement. The data in Table 4-14 show that weight loss of sand plus 2% cement decreases with an increase in

the quantity of EAFD. The weight loss was 9.1 and 7.2% for the sand stabilized with 2% cement plus 20 and 30% EAFD, respectively. The observed weight loss of sand-30% CKD-2% cement is marginally less than that reported by Abdullah [2009], which was about 8%.

Generally, the measured weight loss is less than the allowable weight loss of 14% according to the Portland Cement Association (PCA) [ACI, 1990]. Therefore, it should be noted that the stabilizers and dosages shown in Tables 16 and 17 are satisfactory for stabilizing dune sand from strength and durability perspectives.

Table 17: Weight Loss of Stabilized Sand

Additive Type and Content	Weight Loss (%)
7% Cement	6.1
2% Cement + 30% CKD	6.7
2% Cement + 20% EAFD	9.1
2% Cement + 30% EAFD	7.2

5.4.7 Results of TCLP Tests on the Stabilized Sand

As shown in Table 4.2, EAFD contains toxic metals, such as cadmium, lead and nickel. Since the addition of 30 and 20% EAFD with 2% cement improved the strength of the investigated sand to meet the strength and durability requirements, it is necessary to investigate the leaching of toxic elements to the surrounding environment mainly during rainfall or rise of the ground water table. Therefore, the concentration of toxic elements was measured according to the USEPA (TCLP) procedures [USEPA, 1998]. The results are summarized in Table 4-15.

The data in Table 4-15 indicate the maximum allowable USEPA concentration limits of the toxic metals and the measured concentration of toxic metals in sand stabilized with 2% cement plus 20 or 30% EAFD. The data revealed that, except for silver, the concentration of toxic elements increases with an increase in the quantity of EAFD. The presence of arsenic was not noted since EAFD does not contain this element. The concentration of nickel and vanadium was measured despite the fact that these two elements are not regulated by the USEPA.

The measured concentrations of other elements, regulated by USEPA, were far below the maximum allowable concentrations that are specified by USEPA (EPA limits in Table 3-4). It can be noticed from the data in Table 18 that the concentration of cadmium was 0.819 and 0.969 (mg/l) for the EAFD dosages of 20 and 30%, respectively. The maximum allowable concentration of this element is 1 (mg/l). Thus, the cadmium concentration in sand with 30% EAFD is very close to the allowable limit specified by the USEPA. Consequently, it can be concluded that sand with 2% cement plus more than 30% EAFD may contribute to leaching of cadmium to the environment. Therefore, more than 30% EAFD should not be recommended for stabilizing dune sand that is intended to be used as a base or sub-base course in pavements.

Table 17: TCLP for Sand Stabilized with 2% Cement plus EAFD

Metal		EPA Limits	Measured Values	
			20 % EAFD	30 % EAFD
Name	Symbol	(mg/l)	(mg/l)	(mg/l)
Silver	Ag	5	0.012	0.008
Arsenic	As	5	0000	0000
Barium	Ba	100	1.038	1.133
Cadmium	Cd	1	0.819	0.969
Chromium	Cr	5	0.002	0.003
Mercury	Hg	0.2	0.016	0.018
Lead	Pb	5	0.246	0.186
Selenium	Se	1	0.080	0.092
Nickel	Ni	NR	0.051	0.062
Vanadium	V	NR	0000	0000

NR: Not regulated by EPA

5.4.8 Results of the Unconfined Compression Tests on Sabkha

The unconfined compression tests were carried out to evaluate the effect of the proposed stabilizers and contents on the strength of the investigated sabkha. The correlations between the stabilizer type and content and the UCS are discussed in the following sub-sections.

The results of the unconfined compression test on treated and untreated sabkha are summarized in Table 4-16. The data therein indicate that the UCS of the plain sabkha, 150 kPa, is greater than the UCS of the plain marl, 61 kPa. Though both sabkha and marl soils are classified SM and A-3 according to the USCS and the AASHTO systems, respectively, the low UCS of plain marl could have been due to the high calcite content in the marl [Mohamedzain and Al-Rawas, 2011].

Additionally; the data in Table 18 show that the improvements in the strength of the investigated-stabilized sabkha developed by the indicated stabilizers are lower than

the strength improvements for the stabilized marl. That was attributed to the presence of the halite and gypsum in the sabkha and the presence of the calcite and fine particles in the marl soil.

Moreover; the data in Table 4-16 indicate that sabkha treated with 7% cement and that stabilized with 2% cement plus 30% CKD satisfied the ACI strength requirement for sub-base in rigid pavements. The addition of 30% CKD decreases the quantity of cement from 7 to 2% cement, a reduction of 5% cement. This will lead to economic and environmental benefits.

Table 18: Results of the Unconfined Compression Tests of Sabkha

Additive Type and Content	**UCS (kPa)**		
	Specimen # 1	Specimen # 2	Average
Plain Sabkha (No Additive)	145	155	150
2% Cement	340	356	348
5% Cement	880	916	898
7% Cement	1,481	1,489	1,485
10% CKD	259	265	262
20% CKD	872	880	676
30% CKD	968	980	974
2% Cement + 10% CKD	518	542	530
2% Cement + 20% CKD	887	897	892
2% Cement + 30% CKD	1,516	1,522	1,519
2% Cement + 5% EAFD	0	0	0
2% Cement + 10% EAFD	0	0	0
2% Cement + 20% EAFD	221	229	225
2% Cement + 30% EAFD	318	332	325
2% Cement + 5% OFA	0	0	0
2% Cement + 10% OFA	0	0	0
2% Cement + 15% OFA	136	140	138

5.4.9 Results of the Soaked CBR Tests for Stabilized Sabkha

Specimens of the investigated sabkha were prepared with the dosages of selected stabilizers that satisfied the minimum strength requirements of ACI [1990], and they were subjected to soaked CBR tests. Further, specimens of plain sabkha and with 2, 5 and 7% cement were also tested according to ASTM D 1883. The specimens were sealed and cured for 7 days at laboratory condition (22 ± 3^{o}C). Then, they were soaked in tap water for 96 hours before testing. The effect of each stabilizer on the soaked CBR of sabkha is discussed in the following sub-sections.

The data in Table 19 indicate that the stabilization of sabkha with cement content of 2, 5 and 7% increased the soaked CBR from 11% to 52, 137 and 248%, respectively. The soaked CBR of sabkha with 2% cement plus 10, 20 or 30% CKD was 55, 95 and 129%, respectively. It is obvious that the soaked CBR result of plain sabkha, 11%, was very low, due to the sensitivity of sabkha to water, less than 20%, to be used as a sub-base course in pavements.

Table 1: Results of Soaked CBR of Stabilized Sabkha

Stabilizer Type and Content	**UCS (kPa)**	**Soaked CBR (%)**		
		Specimen #1	Specimen #2	Average
Plain Sabkha (No Additive)	150	9	13	11
2% Cement	348	45	59	52
5% Cement	898	131	143	137
7% Cement	1,485	240	256	248
2% Cement + 10% CKD	530	52	58	55
2% Cement + 20% CKD	892	91	99	95
2% Cement + 30% CKD	1,519	119	139	129

5.4.10 Results of Durability Tests on Stabilized Sabkha

Durability tests were performed to check whether the investigated sabkha stabilized with the selected stabilizers will maintain its stability during long-term exposure to harsh environment. These tests were conducted only on the mixtures that met the strength requirement. Since sabkha mixed with 30% CKD plus 2% cement and that stabilized with only 7% cement met the strength requirements,

ISSN: 2349-6495

durability tests were performed on these two mixes in accordance with ASTM D 559 only on these two mixtures.

The specimens were prepared using the optimum water content determined in the compaction tests. Two specimens were prepared for each mixture. After compaction, the specimens were cured in plastic bags at room temperature for 7 days. The weight loss was determined after 12 cycles of wetting/drying and brushing. The results indicate that for the sabkha soil stabilized with 7% cement, the weight loss was about 8.4% and for the sabkha stabilized with 30% CKD plus 2% cement, the weight loss was about 10.5%. The measured weight loss is less than the maximum allowable weight loss of 14% according to the Portland Cement Association (PCA) and of 11% according to USA Corps of Engineers (USACE) for soils classified as SP and soils having plasticity index (PI) < 10, respectively, ACI [1990].

Therefore, sabkha stabilized with 7% cement or with 30% CKD plus 2% cement can be used as a construction material for sub-base in rigid pavements from strength and durability perspective. However, the use of 30% CKD plus 2% cement will reduce the cement by 5%, which, in turn, lead to economic and environmental benefits.

5.5 Summary of the Results of the Stabilized Soils

The stabilized soils that met the strength requirements and satisfied the durability limits are summarized in Table 20.

The data in Table 20 summarize the general findings of this investigation. This table helps engineers to choose the appropriate stabilizer and dosage to stabilize eastern Saudi soils to be used as effective construction materials in pavement construction.

Table 20 Summary of the Stabilized Soils

Stabilizer Types and Contents	**Soil**	**layer**	**Pavement**
7% Cement	Non-Plastic Marl	Base	Rigid
	Sabkha and Sand	Sub-base	Rigid
5% cement	Non-Plastic Marl	Sub-base	Flexible
2% Cement + 30% CKD	Non-Plastic Marl	Sub-base	Flexible
	Sand and Sabkha	Sub-base	Rigid
2% Cement + 20% EAFD	Non-Plastic Marl and Sand	Sub-base	Rigid
2% Cement + 30% EAFD	Non-Plastic Marl and Sand	Sub-base	Flexible

5.6 Economic Advantage

It is well known that cement, being the most commonly used conventional soil stabilizing agent, is not only expensive but also its production consumes a lot of energy. Further, the manufacturing process of cement results in greenhouse gases that is not environment-friendly. Therefore, there are concerted efforts worldwide to use materials other than cement for construction purposes. However, the used materials have to be cost effective and eco-friendly.

Since only flexible pavements are used in Saudi Arabia, cost estimate for producing 100 m^3 of stabilized soils in sub-bases in flexible pavements, utilizing cement, 2% cement plus CKD or EAFD was conducted. The amount of stabilizers required to satisfy an UCS of 1,725 kPa was predicted using the models developed for each stabilizing material. The project site (where the pavement was assumed to be constructed) was located in Dhahran area. The price of one ton of cement was assumed to be SR 300. Other materials, such as CKD and EAFD were considered for free (as waste materials) with loading cost of 5 SR/ton and transportation cost of 10 SR/ton. The transportation cost of material from Jubail to the site was estimated to be SR 300 for a truck of 30 ton capacity. The dry unit weight was either interpolated or taken from the data in Table 10.

Table 21 shows the amount of cement required to achieve UCS of 1,725 kPa for non-plastic marl, dune sand and sabkha using. The cost of cement required to stabilize 100 m^3 of these soils for use in sub-base of flexible pavements was estimated. The cost of cement in marl, sand and sabkha was SR 1,980, 4,130 and 4,390, respectively.

Table 21: Cost of Cement for Stabilizing 100 m^3 Sub-Base Course in Flexible Pavements

Stabilized Soil	Dry Unit Weight	Soil	Cement	Cement	Cost
	ton/m^3	m^3	(%)	(ton)	SR
Non-Plastic Marl	1.89	100	3.5	6.62	1,980
Dune Sand	1.72	100	7.5	13.76	4,130
Arabian Gulf Sabkha	1.95	100	8	14.63	4,390

The amount of soils (marl, sand and sabkha) was estimated considering the volume of CKD added to soils in order to have total volume of stabilized soils of 100 m^3. The material

ISSN: 2349-6495

cost of 100 m^3 of marl, sand and sabkha stabilized with 2% cement plus CKD is shown in Table 4-20. The cost is SR 1,590, 1,690 and 1,625, respectively. Comparing the cost of stabilization with only cement (Table 22), to that utilizing 2% cement plus CKD (Table 4-20) it is evident that the use of CKD would lead to saving of 20, 60 and 63% for marl, sand and sabkha, respectively.

Table 22: Cost of 2% Cement plus CKD for Stabilizing 100 m^3 Sub-Base Course in Flexible Pavements

Stabilized Soil	Dry Unit Weight	Soil	CKD	2% Cement	CKD	Cost	Reduction
	ton/m^3	m^3	(%)	(ton)	(ton)	SR	(%)
Non-Plastic Marl	2	80	30	3.02	45.4	1,590	20
Dune Sand	2	85	37	2.92	54.1	1,690	60
Arabian Gulf Sabkha	1.9	75	34	2.93	49.7	1,625	63

Similarly; the quantity of EAFD required for stabilizing marl and sand (sabkha soil with EAFD failed to satisfy the strength requirement) was determined. Table 23 shows the materials and cost of 100 m^3 of marl and sand stabilized with 2% cement plus EAFD. The cost is SR 1,690 and 1,620, respectively. Comparing the cost of stabilizing the investigated soil with only cement (Table 21) to that utilizing 2% cement plus EAFD (Table 23), it could be easily noted that the use of EAFD leads to saving of 15 and 61% for marl and sand, respectively.

Table 23: Cost of 2% Cement plus EAFD for Stabilizing 100 m^3 Sub-Base Course in Flexible Pavements

Stabilized Soil	Dry Unit Weight	Soil	EAFD	2% Cement	EAFD	Cost	Reduction
	ton/m^3	m^3	(%)	(ton)	(ton)	SR	(%)
Non-Plastic Marl	2.2	93	24	3.52	42.2	1,690	15
Dune Sand	2.2	95	26	3.27	42.5	1,620	61

Note: EAFD did not improve the UCS of sabkha

Therefore, reducing the amount of cement required for stabilizing the three indigenous soils was the direct benefit of using by-products in the stabilization of local soils. Furthermore, there are indirect benefits of using by-products in stabilization of weak soils. Reducing the needed energy for producing cement contributes to mitigating the amount of the greenhouse gases and the consequent positive environment effects. Moreover, while some by-products contain volatile gases which cause air pollution, other contains heavy metals which cause land and ground water contamination. Consequently, the disposal of these by-products is costly. Therefore, using contaminant by-products for soil stabilization will result in avoiding the disposal cost and in meeting the environmental requirements. Consequently, the priceless outcome of using theses waste materials in stabilizing indigenous eastern Saudi soils is keeping sound-environment.

VI. CONCLUSIONS

This research was designed to stabilize three eastern Saudi soils, namely non-plastic marl, dune sand and sabkha. The potentiality of using stabilizers, cement, as a reference, and other industrial by-products in improving the properties of these soils was investigated. The stabilizing by-products included oil fuel ash (OFA), cement kiln dust (CKD) and electric arc furnace dust (EAFD).

Characterization of the investigated soils was performed including specific gravity, Atterberg limits, grain-size distribution and mineralogical composition. Further, specific gravity and chemical composition of the candidate stabilizers were determined.

The optimum moisture content corresponding to the maximum dry density of the investigated soils without and with the proposed dosages of the three stabilizers was determined using the modified Proctor compaction. Specimens of parent and stabilized soils were prepared with the optimum moisture content. The evaluation of the improvement of the three soils was performed by macro-characterization and micro-characterization techniques.

Macro-characterization study including unconfined compression, soaked CBR and durability tests were conducted to assess the engineering properties of treated and untreated soils. The environmental impact of the stabilizers containing toxic elements and succeeded to improve the soils to meet the ACI requirements for usage in pavement structures was studied using TCLP tests.

Micro-characterization study using XRD and/or SEM devices was utilized to depict qualitatively the mechanisms of improvement of the soils by the additives.

Based on the interpretation of the results presented in this research, the following main conclusions could be drawn:

(i) Cement was found to be superior in stabilizing the three local soils from strength and durability points of view.

(ii) As the CKD and the EAFD contents plus 2% cement increased, the strength and the soaked CBR of stabilized marl and sand increased.

(iii) CKD content alone was not adequate for effective stabilization of dune sand, non-plastic marl and sabkha soils. Even 30% CKD did not meet the ACI strength requirements.

(iv) Micro-characterization techniques utilizing BEI and SEM showed, in the case of using 2% cement plus CKD in stabilizing the three soils, more fibrous formations in the three stabilized soils than that with 2% cement alone which contributed to the high improvement in the UCS to meet the ACI requirements.

(v) The stabilized soils with any stabilizer that satisfied the minimum strength and CBR requirements satisfied also the durability requirements.

(vi) 20 and 30% EAFD with 2% cement were adequate for effective stabilization of non-plastic marl and sand to be used as construction material for sub-base in rigid and flexible pavements.

(vii) Ankerite and wustite formations in marl stabilized with 2% cement plus EAFD were found to be the primary cementing product in theses mixtures.

(viii) Wustite formation in sand stabilized with 2% cement plus EAFD was found to be the principal cementing product in theses mixtures.

(ix) None of the EAFD contents plus 2% cement was effective in the stabilization of sabkha.

(x) OFA plus 2% cement was not a suitable stabilizer for any of the investigated eastern Saudi soils.

(xi) TCLP tests results indicated that the investigated industrial by-products that satisfied the strength requirements were eco-friendly within the dosages reported herein.

(xii) Economic analysis indicated that the use of these industrial by-products for stabilizing eastern Saudi soils is cost effective, particularly for stabilizing sand and sabkha soils.

VII. RECOMMENDATIONS

- 7% cement was found to be the proper stabilizer for dune sand and sabkha to be used as a sub-base course in rigid pavements and for non-plastic marl to be used as a base course in rigid pavements.
- 5% cement was a suitable stabilizer for non-plastic marl to be used as a sub-base in flexible and rigid pavements.
- A CKD content of 30% plus 2% cement was found to be adequate for the effective stabilization of non-plastic marl soils to be used as a base course in flexible pavements and of dune sand and sabkha soils to be used as a sub-base course in rigid pavements. It met the strength and durability requirements.
- EAFD contents of 20 and 30% plus 2% cement were found to be adequate for the effective stabilization of dune sand and non-plastic marl soils to be used as a sub-base in rigid and flexible pavements, respectively.
- The developed correlative equations between the stabilizer type and content with the UCS and the soaked CBR of the stabilized soils are summarized in Tables 24through 26. These equations help the practicing engineers select and estimate the appropriate dosage of the industrial by-product(s) in terms of strength and soaked CBR.

Table 24: Correlation between UCS and Soaked CBR and the Stabilizer Contents for Eastern Saudi Non-Plastic Marl (7-Day Sealed Curing)

Stabilizer Type	**Non-Plastic Marl**	
	UCS (kPa)	**Soaked CBR (%)**
Cement	$509.8 *X + 61$, $R^2 = 0.96$	$13.12*e^{0.569X}$, $R^2 = 0.97$
2% Cement + CKD	$657.76 * e^{0.034X}$, $R^2 = 0.99$	$56.88*e^{0.051X}$,$R^2 = 0.96$
2% Cement + EAFD	$523.32\ e^{0.051X}$, $R^2 = 1$	$8.08*X + 95$, $R^2 = 0.89$
Soaked CBR (%) = $0.14*$ UCS (kPa) +11, $R^2 = 0.88$		

Table 25: Correlation between UCS and Soaked CBR and the Stabilizer Contents for Eastern Saudi Dune Sand (7-Day Sealed Curing)

Stabilizer Type	**Dune Sand**	
	UCS (kPa)	**Soaked CBR (%)**
Cement	$228.12*X$, $R^2 = 0.97$	$113.7*e^{0.184X}$, $R^2 = 0.95$
2% Cement + CKD	$321.72*e^{0.046X}$, $R^2 = 0.94$	$157.9*e^{0.029X}$, $R^2 = 0.94$
2% Cement + EAFD	$313.94*e^{0.068X}$, $R^2 = 0.97$	$176.15*e^{0.052X}$, $R^2 = 0.92$

Soaked CBR (%) = 0.25* UCS (kPa)+103 , R^2 = 0.83

Table 26: Correlation between UCS and Soaked CBR and the Stabilizer Contents for Eastern Saudi Sabkha (7-Day Sealed Curing)

Stabilizer Type	Sabkha	
	UCS (kPa)	**Soaked CBR (%)**
Cement	$164.19 e^{0.326X}$, R^2 = 0.99	$30.4X + 11$, R^2 = 0.94
2% Cement + CKD	$336.8 e^{0.049X}$, R^2 = 1	$46.79 e^{0.033X}$, R^2 = 0.87
Soaked CBR (%) = 0.13* UCS (kPa) , R^2 =0.76		

Conditions for Tables 5-1 through 5-3:

- X is the weight content of stabilizer to the dry weight of soil (%).
- The mixtures are to be prepared at the optimum moisture contents using modified Proctor compaction energy.

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